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14. ABSTRACT

Minnesat is the micro-satellite that was designed by the University of Minnesota as part of UNP-4. The mission of Minnesat was to validate the use carrier phase GPS technology to mechanize a compact and accurate attitude determination system. In a broader sense, the objective of this work was to also demonstrate a design methodology for miniature spacecraft navigation, guidance and control systems which integrate the vehicle design process with that of the process of designing the avionics. Minnesat was presented to the US Air Force at the UNP-4 flight competition review. Although Minnesat was not the winning design, it accomplished its scientific and educational goals. The research work of designing compact GPS attitude determination systems continues at the University of Minnesota building on the success of Minnesat. On the other hand, students that were participants in the UNP-4 competition are now employed by various aerospace corporations, are enrolled in aerospace engineering graduate programs or are completing advanced degrees in engineering and science programs.

15. SUBJECT TERMS

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EXECUTIVE SUMMARY

This summarizes the work done under AFOSR Grant FA9550-05-1-0327 at the University of Minnesota, Twin Cities Campus from April 2005 to April 2007. This grant supported the University of Minnesota's participation in the University Nanosat Program fourth competition cycle (UNP-4). Minnesat is the micro-satellite that was designed by the University of Minnesota as part of UNP-4. The mission of Minnesat was to validate the use carrier phase GPS technology to mechanize a compact and accurate attitude determination system. In a broader sense, the objective of this work was to also demonstrate a design methodology for miniature spacecraft navigation, guidance and control systems which integrate the vehicle design process with that of the process of designing the avionics.

Minnesat was presented to the US Air Force at the UNP-4 flight competition review. Although Minnesat was not the winning design, it accomplished its scientific and educational goals. The research work of designing compact GPS attitude determination systems continues at the University of Minnesota building on the success of Minnesat. On the other hand, students that were participants in the UNP-4 competition are now employed by various aerospace corporations, are enrolled in aerospace engineering graduate programs or are completing advanced degrees in engineering and science programs.

1. GRANT/PROJECT OVERVIEW

The US Air Force (USAF) University Nanosat Program is a joint program run by the Air Force Research Laboratory's Space Vehicle Directorate (AFRL/VS), the Air Force Office of Scientific Research (AFOSR), American Institute of Aeronautics and Astronautics (AIAA) and the National Aeronautics and Space Administration (NASA). The major objective of the program is to educate and train the future workforce that will be responsible for the design and operation of miniature satellites. A secondary objective of the program is to explore satellite research problems that are of current interest to the US Air Force and NASA.

The program achieves these dual goals by a national student satellite design and fabrication competition. The competition involves eleven universities where each university team must design a space-worthy nano-satellite (or nanosat for short) to perform a science experiment which addresses a problem of current interest to the USAF and NASA. At the end of the competition a single winner is selected by a panel of experts. The winning nanosat design is launched by the USAF and the winning team gets to conduct their experiment on orbit.

Minnesat is the University of Minnesota's entry into the USAF University Nanosat Program and its science mission is to explore a novel method of orientation (or attitude) determination for miniature satellites. Minnesat will be exploring a technique of attitude determination where signals from the Global Positioning System (GPS) satellites are used like a radio interferometer. Making such radio interferometers work on miniature satellites such as Minnesat requires, in part, developing methods for precise calibration of GPS antenna gain patterns.

For its science mission it will carry eight GPS antenna/receiver pairs which form the interferometer. One antenna is located on each face of the satellite. The satellite also has various other systems such as the power management system, a flight computer system, and communication system which are there to support the science experiment.

The Minnesat team consists of 20 students (both undergraduate and graduate from various departments in IT) and 3 faculty members from the Aerospace and Electrical Engineering Departments. Design and analysis of most of the satellite's systems have been completed and the team has commenced prototyping and building the actual space qualified hardware. Final selection of winning design will occur in March 2007.

THE MINNESAT TEAM

The Minnesat team consists of students and faculty from a range of engineering disciplines. The students range from undergraduates to Ph.D. candidates. Since the emphasis of the project is on student education, students are involved in every aspect of the project, from top level management through design, fabrication, and testing. The experience that students gain while participating in this project will help them in further academic and professional endeavors.

Minnesat is the first complete satellite design performed at the University of Minnesota. The Minnesat team will give the University of Minnesota experience in satellite design as well as help establish a heritage program of spacecraft design. This will allow the University to pursue more ambitious satellite projects in the future.

THE MINNESAT MISSION

The mission of Minnesat is to develop, fabricate, test, and fly a short baseline Global Positioning System (GPS) attitude determination system in low Earth orbit. The system will consist of several GPS antennas and receivers positioned on the spacecraft. Using the differences in the signals received by the different antennas, we will compute the spacecraft's attitude. Because the antennas are located close to one another, the problem is very complex and difficult. In order to increase the bandwidth of the system, an inertial measurement unit (IMU) will augment the GPS receivers. The accuracy of the GPS system will be verified by an independent attitude determination system consisting of an IMU and a 3-axis magnetometer.

THE SPACECRAFT

The Minnesat spacecraft must meet all UN-4 program constraints & requirements, which are specified in the UN-4 User's Guide. The most notable constraints state that the spacecraft must fit within a physical envelope consisting of a right circular cylinder 45 cm in diameter and 45 cm in height, and must have a mass of less than 30 kg. Minnesat is designed solely to accommodate the GPS attitude determination system in low Earth orbit. Minnesat consists of six systems, each serving a specific function vital to the mission. These systems are the flight computing system, power system, communication system, attitude determination system, structure system, and thermal system. All systems exist either to support the GPS mission or to meet UN-4 program requirements.

Flight Computing System

The flight computing system is responsible for all computing on board the spacecraft. The system consists of two PC-104 computer boards. Each computer will perform all of the computations necessary to compute the attitude and navigation solutions, control the spacecraft, communicate with the ground station, and troubleshoot any problems on board. In the event that one computer fails the second will take over, allowing Minnesat to continue its mission.

Power Management System

The power management system is responsible for providing electrical power to every system on board the spacecraft. It consists of solar cells for collecting energy, rechargeable batteries for providing power during eclipse and during periods of peak power draw, regulators and busses to distribute power to the other systems, and a power manager microcontroller to oversee the battery charging and maintain the system health.

Communications System

The communications system is responsible for maintaining contact with the ground. It will consist of two transceivers using amateur radio frequencies (435 MHz) for uplink and downlink as well as several antennas.

Attitude Determination and Navigation System

The attitude determination, navigation, and control system consists of two subsystems, the GPS subsystem and the primary attitude subsystem. The GPS subsystem is the science mission of Minnesat, and will determine the attitude of Minnesat using several GPS receivers working together. The primary attitude subsystem will determine Minnesat's attitude using conventional sensors proven to work in space. Specifically, an Inertial Measurement Unit (IMU) aided by triad of magnetometers and a dynamic model of the satellite will provide the primary attitude solution. This will provide a baseline against which to compare the GPS attitude system results.

Structure System

The structure system holds every other system together. It is responsible for ensuring the survival and integrity of the spacecraft during launch and while on-orbit. It will consist of an aluminum frame with component boxes to house other systems.

Health Monitoring and Control System

The health monitoring and control system is responsible for maintaining all components within their operating temperature range. The system consists of sensors to determine if a component requires heat, resistive heaters for heating, logic to control the heaters, and other passive heating or cooling elements such as heat sinks and conductive finishes.

2. PUBLICATIONS

The research work supported by this grant led to the publication of the following three papers:

1. D. Gebre-Egziabher "Magnetometer Auto-Calibration Leveraging Measurement Locus Constraints," AIAA *Journal of Aircraft*, Vol. 44, No. 4. pp. 1361 – 1368.

2. V. L. Bageshwar, D. Gebre-Egziabher, W. Garrard, J. Mintz, *et. al.*,"Minnesat: GPS Attitude Determination Experiments Onboard a Nanosatellite," *Proceedings of the 20th Annual Small Satellite Conference*. Logan, UT, Aug. 2006.

3. V. L. Bageshwar, D. Gebre-Egziabher, W. Garrard, P. Shestople, and M. Adams, "Inertially Aided Vector Matching Algorithm for Satellite Attitude Determination," in preparation for submission to *AIAA Journal of Guidance, Control and Dynamics.*

3. TECHNICAL PROGRAM AND RESEARCH CONTRIBUTIONS

Minnesat will demonstrate new technology in several areas. We will make scientific advances in attitude determination using a miniature multi-sensor system which combines magnetometers, gyroscopes, and GPS in order to determine the spacecraft's attitude quickly and accurately. This system could easily be incorporated into other spacecraft which require a low cost, small, and lightweight attitude determination system. The GPS aspect of attitude determination will be an improvement over existing GPS systems, with advances in mitigating problems from multipath, phase center motion, and phase ambiguity.

Minnesat will also use new and innovative methods of spacecraft design, fabrication, and testing. This is not a stated program objective, but comes as a necessity due to the nature of the UN-4 program. Whereas a conventional satellite may take several years, hundreds of people, and millions of dollars to complete, Minnesat will be completed in less than two years by a team of several dozen students working part time on the project and with a significantly smaller budget. This forces the team to use off-the-shelf products in innovative ways in order to speed up the design process and reduce costs. This technology may eventually be applied to other nanosatellites or full-sized spacecraft.

ATTITUDE DETERMINATION OVERVIEW

Attitude refers to a vehicle's angular orientation in space. The attitude of a vehicle can be defined by specifying the relative orientation of two reference frames. For spacecraft guidance, navigation, and control applications in Earth orbit, the two reference frames typically used are a vehicle fixed body frame and a navigation frame with known orientation. The navigation frame generally refers to an inertial frame, an Earth-fixed frame, or a local vertical local horizontal frame and its selection depends on the application. Attitude determination (AD) systems are used to estimate the orientation of a vehicle or, more specifically, to estimate the relative orientation of the two reference frames.

An AD system consists of a set of sensors to measure the vehicle's attitude and a filter that blends the sensor measurements to estimate the vehicle's attitude. The attitude sensors typically used in spacecraft AD systems include inertial sensors, star trackers, Sun sensors, and horizon sensors. The selection of an attitude sensor depends on several factors including its size, mass, power consumption, and performance characteristics. Nanosatellites are a class of miniature satellites that have severe restrictions on size, mass, and available power. These restrictions effectively become restrictions on attitude sensors and, thus, limit the selection of attitude sensors that can be used for nanosatellite AD systems.

Recently, the Global Positioning System (GPS) has been used to estimate the attitude of vehicles in aerospace applications. AD systems designed using GPS require multiple GPS sensors onboard the vehicle. A GPS sensor consists of an antenna to measure the signal carrier broadcast by GPS satellites and a receiver to collect and process the signals measured by the antenna. The size, mass, and power consumption of a typical GPS sensor satisfy the restrictions of a nanosatellite. Therefore, GPS sensors have the potential to be used as attitude sensors for nanosatellite AD systems.

GPS AD systems use carrier phase measurements from multiple antennas separated by distances referred to as baselines.[1] The performance of GPS AD systems depends on several factors including the relative distance between antennas. These antennas are arranged in configurations where the lengths of the baselines are at least several integer cycles longer than the wavelength (~19 cm) of the GPS signal carrier. These antenna baseline lengths are selected to mitigate the effect of measurement errors of a GPS sensor.

GPS sensor measurement errors include both uncorrelated and correlated components.[2] The uncorrelated errors refer to wide band noise. These errors are due to thermal noise in the signal channel and the GPS receiver. The correlated errors refer to the phase delay of the GPS antenna. The effect of the phase delay becomes more significant as the antenna baseline lengths approach the wavelength of the GPS signal carrier. Current GPS AD systems do not incorporate models of the antenna correlated errors. Therefore, the performance of these AD systems depends on the antenna baseline lengths and whether the phase delay contributes significantly to the measurement errors of the GPS signal carrier.

Current GPS AD systems are used on aerospace vehicles much larger than nanosatellites. These AD systems require the vehicles to support antenna baselines longer than the dimensions of nanosatellites and aerospace vehicles of similar size. However, if accurate models of the antenna correlated errors can be developed and incorporated into GPS AD systems, then these AD systems could estimate attitude using shorter antenna baselines. Furthermore, these AD systems could be used for applications where shorter antenna baselines are necessary.

The University of Minnesota Small Satellite Program is currently designing a nanosatellite called Minnesat. Minnesat is the University of Minnesota's entry into the AFRL, AIAA, & AFOSR University Nanosat-4 competition. The scientific mission of the Minnesat project is to design and evaluate the performance of an ultra-short baseline GPS AD system. The objectives of this mission are to investigate the hardware modifications required for operation of GPS sensors using ultra-short baselines in Earth orbit; to design and validate models for the antenna correlated errors; to design and validate the algorithms required to mechanize an attitude filter for the ultra-short baseline GPS AD system; and to evaluate the accuracy of the attitude estimates computed by the attitude filter. The Minnesat project is a student managed and operated project and, thus, the cost of components is an important design constraint for every system. Therefore, inexpensive, commercial-off-the-shelf components are used throughout the design of Minnesat.

This paper presents an overview of Minnesat's scientific mission and is organized as follows. First, we describe the fundamentals of GPS attitude determination. This description is limited to top-level details and the technical details will be presented in a following paper. Second, we describe the GPS antenna configuration supported by Minnesat's frame. Third, we briefly describe Minnesat's systems and operation. Fourth, we describe the Kalman filters designed to estimate Minnesat's attitude.

GPS ATTITUDE DETERMINATION FUNDAMENTALS

The attitude of a vehicle can be computed by considering three fixed non-collinear points on the vehicle. In general, three non-collinear points in space define a plane. If the positions of these three points are known in the vehicle's body frame, then the orientation of this plane can be uniquely defined in this body frame. Furthermore, if the positions of these three points are known in the navigation frame, then the orientation of this plane and body frame can be computed relative to the navigation frame.

GPS AD systems make use of this principle to estimate a vehicle's attitude in the following manner. Three non-collinear GPS antennas are mounted on the structure of a vehicle such that their positions are always known in the vehicle's body frame. Therefore, these three antennas define three fixed baselines and a fixed plane in the vehicle's body frame. The positions of the antennas are measured using GPS carrier phase signals and their relative positions are estimated using differential carrier phase GPS (CDGPS) techniques. These differential carrier phase measurements (dCPMs) are used to estimate the orientation of the fixed plane and, thus, the vehicle's body frame relative to the navigation frame.

CDGPS techniques are based on subtracting the carrier phase measurements of two antennas that are tracking common GPS satellites. These dCPMs provide an estimate of the phase difference between GPS signals measured by the two antennas. This phase difference provides an estimate of the relative position, or delta range, of the two antennas along the line-of-sight (LOS) vector from the antenna baseline to a GPS satellite (Figure 1). There exists a geometric relationship between the antenna baseline vector, the LOS vector, and the delta range. If the two antennas are tracking four common GPS satellites, then this geometric relationship can be used to determine the direction of the antenna baseline vector. A second antenna baseline is required to resolve the rotational ambiguity in the direction of the first antenna baseline vector. The third antenna baseline is redundant because only two antenna baselines are required to determine attitude.

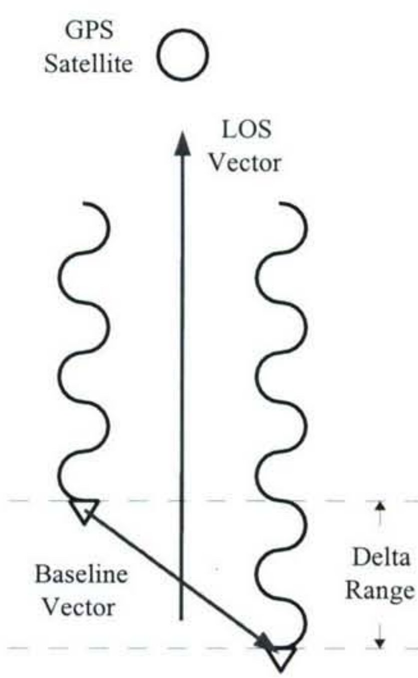

Figure 1. GPS Antenna Baseline Geometry

The dCPMs of an antenna baseline are corrupted by several errors that must be calibrated before the attitude filter can use these measurements to compute estimates of a vehicle's attitude. These measurement errors include integer ambiguities, line bias, multipath noise, and antenna phase delay.[3] The advantage of using dCPMs is that they eliminate common mode errors of the carrier phase measurements. These first three error sources have been the subject of intense recent research. The fourth error source is the subject of research for the Minnesat project. The resolution of these errors is referred to as the calibration procedure for the dCPMs.

Integer ambiguity refers to the whole number of signal carrier cycles that exist in the dCPMs. The range of the integer ambiguity space depends on the length of the antenna baseline and the wavelength of the GPS signal carrier. The L1 GPS signal carrier has a frequency of 1575.42 MHz corresponding to a wavelength of 19.03 cm. Therefore, as the length of the antenna baseline increases, the range of the integer ambiguity space increases and the time required to resolve the integer ambiguity for dCPMs increases as well. The integer ambiguity must be resolved for each GPS satellite tracked by the two antennas that form the baseline.

Line bias refers to the time delay a measured GPS signal experiences between the antenna and its corresponding receiver. The line bias is generally assumed to be slowly time varying and is dependent on several factors including temperature. The line bias is independent of the GPS satellite constellation and the attitude of the vehicle. Multipath noise refers to GPS signals measured from reflective surfaces around the GPS antenna.

The phase delay refers to delays that result from the misalignment of the geometric centroid of the antenna and the phase measurement center. This delay depends on the LOS vector from the antenna baseline to the GPS satellite and on the size of the antenna. This delay becomes more significant as the length of the antenna baseline approaches the wavelength of the GPS signal carrier. This delay is time varying because the LOS vector depends on the position of the GPS satellite and the attitude of the vehicle. This delay can be resolved by generating an *a priori* lookup table that lists estimates of the phase delay for the azimuth and elevation angles of an arbitrary LOS vector.[4] The azimuth angle of the LOS vector ranges from 0° to 360°. The elevation angle of the LOS vector ranges from 0° to 90°. In summary, the calibration procedure for dCPMs requires resolution of the integer ambiguities, resolution of the line bias, and adjustment for the phase delay using a lookup table.

Current GPS AD systems use long antenna baselines where the baseline lengths are several integer cycles longer than the wavelength of the L1 GPS signal carrier. The advantages of using long antenna baselines as compared to short antenna baselines are that the measurement errors introduced by thermal noise and differential phase delay are negligible. Therefore, AD systems that do not account for these measurement errors are more accurate. The disadvantages of using long antenna baselines as compared to short antenna baselines are as follows. First, the range of the integer ambiguity space increases so that more time is required to resolve the integer ambiguities and calibrate the dCPMs. Second, the size of the vehicle must support the long antenna baselines. Nanosatellites, and aerospace vehicles of similar size, do not have sufficient rigid surface area to support long antenna baselines. It is possible to mount antennas on extendable booms from the nanosatellite. However, antennas mounted on these booms are subject to the vibrational modes of the boom that would add an additional error source to the dCPMs and would affect the accuracy of the attitude estimates.

GPS ANTENNA CONFIGURATION

The University of Minnesota nanosatellite, Minnesat, is designed as a test bed for conducting ultra-short baseline GPS attitude determination experiments in Earth orbit. Minnesat's frame supports a GPS antenna configuration that is designed to ensure that at least two antenna baselines are available for attitude determination regardless of its orientation or orbital position. The guidelines of the University Nanosat-4 competition constrain the physical dimensions of Minnesat to fit within a physical envelope defined by a circular cylinder of diameter 48 cm and height 48 cm and to weight less than 30 kg.

Minnesat has an axisymmetric hexagonal frame with a circumscribed radius of 22.5 cm and with a height of 45 cm. One GPS antenna is mounted at the center of each side of the frame for a total of eight GPS antennas onboard Minnesat. Figure 2 shows a schematic of Minnesat. The GPS antennas are represented by light colored boxes at the center of each side of the satellite. Solar cells are represented by dark blue boxes on each side of the satellite. The design trade-offs for the frame design and antenna configuration are influenced by several factors including the number of antenna baselines available for attitude determination; the antenna baseline redundancy in the event of GPS sensor failure; the additional volume, mass, power, and cost required to support one GPS sensor; and the available surface area for placement of GPS antennas and solar cells.

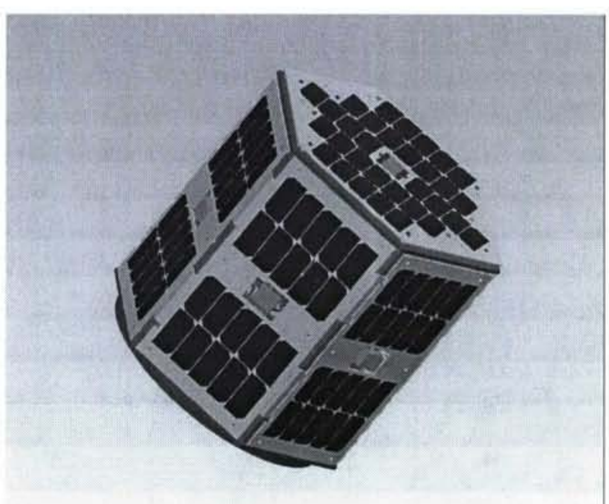

Figure 2. Minnesat Schematic

This GPS antenna configuration supports twenty eight possible antenna baselines. However, antennas located on opposite sides of the frame can not form a baseline for attitude determination. For example, Figure 3 shows that antennas mounted on sides 3 and 6 of the frame will not have common visible GPS satellites. Figure 4 shows that this antenna configuration supports twenty four antenna baselines for attitude determination. Antennas located on sides 1 and 8 of the frame can form baselines with antennas

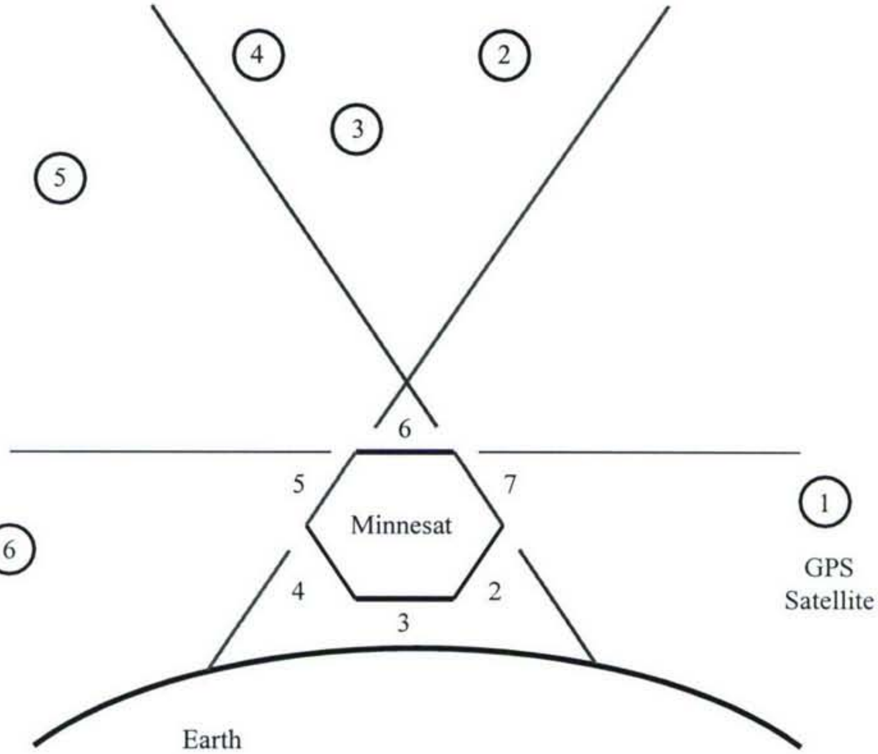

Figure 3. Visible GPS Satellites

located on adjacent sides of the frame for a total of six baselines each. Antennas located on sides 2 through 6 of the frame can form baselines with any antenna except those located on opposite sides of the frame. This antenna configuration supports three baseline lengths: 19.5 cm, 31.8 cm, and 33.8 cm. For the L1 GPS signal carrier, the integer ambiguities of dCPMs for these three antenna baselines are -1, 0, and 1, only. Table 1 summarizes the available antenna baselines for attitude determination. A red × indicates that the baseline formed using these antennas can not be used for attitude determination.

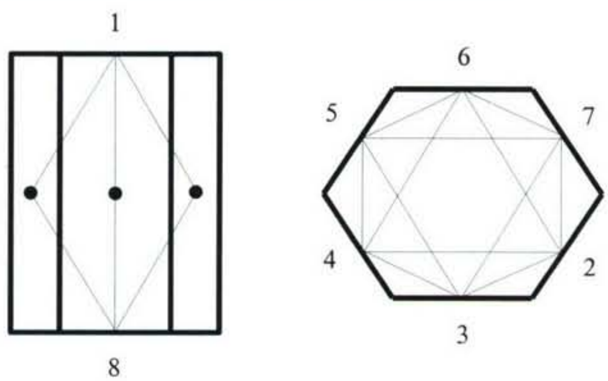

Figure 4. GPS Antenna Baselines

Table 1. GPS Antenna Baseline Lengths

GPS Sensor	1	2	3	4	5	6	7	8
1	×	31.8 cm	31.8 cm	31.8 cm	31.8 cm	31.8 cm	31.8 cm	×
2	31.8 cm	×	19.5 cm	33.8 cm	×	33.8 cm	19.5 cm	31.8 cm
3	31.8 cm	19.5 cm	×	19.5 cm	33.8 cm	×	33.8 cm	31.8 cm
4	31.8 cm	33.8 cm	19.5 cm	×	19.5 cm	33.8 cm	×	31.8 cm
5	31.8 cm	×	33.8 cm	19.5 cm	×	19.5 cm	33.8 cm	31.8 cm
6	31.8 cm	33.8 cm	×	33.8 cm	19.5 cm	×	19.5 cm	31.8 cm
7	31.8 cm	19.5 cm	33.8 cm	×	33.8 cm	19.5 cm	×	31.8 cm
8	×	31.8 cm	31.8 cm	31.8 cm	31.8 cm	31.8 cm	31.8 cm	×

Minnesat's GPS antenna configuration is selected to ensure that more than two baselines are available for the GPS AD system regardless of Minnesat's orientation or orbital position. Therefore, Minnesat does not require an attitude control system and control actuators to continuously point the satellite so that the same two antenna baselines are used for attitude determination. Furthermore, onboard CPU processing time, mass, and power do not have to be allocated to an attitude control system and control actuators. It should be noted that the moments of inertia are selected to ensure that Minnesat is dynamically stable.

MINNESAT MISSION OVERVIEW

Minnesat is equipped with multiple sensors and components to support two real-time AD systems and a real-time navigation system (Figure 5). The two AD systems are referred to as the Primary AD System and the GPS AD System.

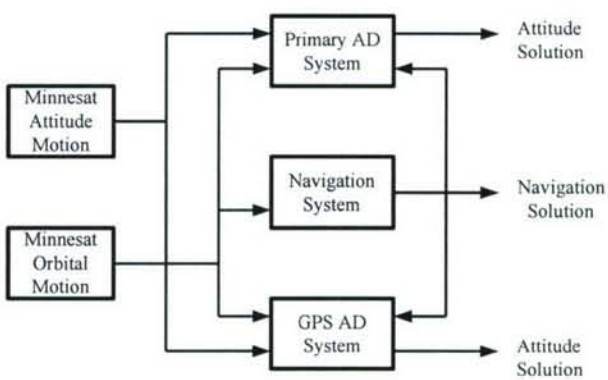

Figure 5. Mission Overview

The Primary AD System (Figure 6) consists of rate gyros, a three-axis magnetometer, a magnetometer calibration procedure, and an extended Kalman filter (EKF). The EKF blends measurements of the rate gyros with calibrated magnetometer measurements to compute real-time estimates of Minnesat's attitude. The GPS AD System (Figure 7) consists of rate gyros, multiple GPS sensors, the dCPM calibration procedure, and an EKF. The EKF blends measurements of the rate gyros with calibrated dCPMs to compute real-time estimates of Minnesat's attitude. The rate gyros are used to increase the filter bandwidth for both AD systems as compared to using the magnetometer or GPS sensors individually.

The attitude estimates computed using the Primary AD System are used to establish a baseline for filter performance. The performance of the GPS AD System can then be evaluated by comparing its attitude estimates to the baseline filter performance. It should be noted that the visible GPS satellite constellation depends on time and Minnesat's orbital position. The effect of the visible GPS satellite constellation on the accuracy of the dCPMs can be quantified through the attitude dilution of precision (ADOP). Therefore, the performance of the GPS AD System is also evaluated as a function of ADOP.

The Navigation System (Figure 8) uses the GPS navigation messages to estimate Minnesat's current orbital position, to predict Minnesat's orbit, and to estimate the orbital positions of the GPS satellite constellation. Minnesat's orbital position is used by the Primary AD System to estimate the local Earth magnetic field vector for its EKF. Minnesat's predicted orbit is used to estimate when ground communication is possible with Minnesat's Ground Station System located in Minneapolis. The orbital positions of the GPS satellite constellation are used by the GPS AD System to estimate the LOS vector from an antenna baseline to a visible GPS satellite.

Minnesat transmits both attitude and navigation data to the Ground Station System during ground communication windows. The attitude and navigation data consists of sensor measurements, selected data from the GPS navigation messages, the Navigation System position data, the Primary AD System calibration and attitude filter data, and the GPS AD System calibration and attitude filter data. These data sets are time stamped, compressed, and stored in onboard archival memory in the form of data packets. These data packets are then sequentially transmitted to the Ground Station System for processing.

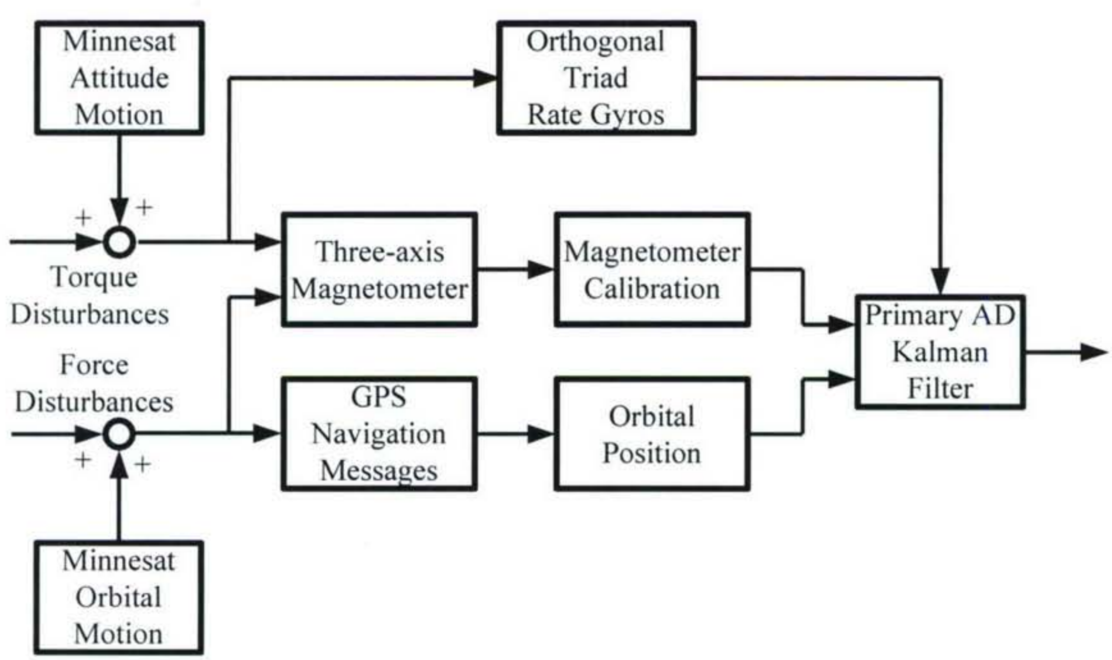

Figure 6. Primary AD System

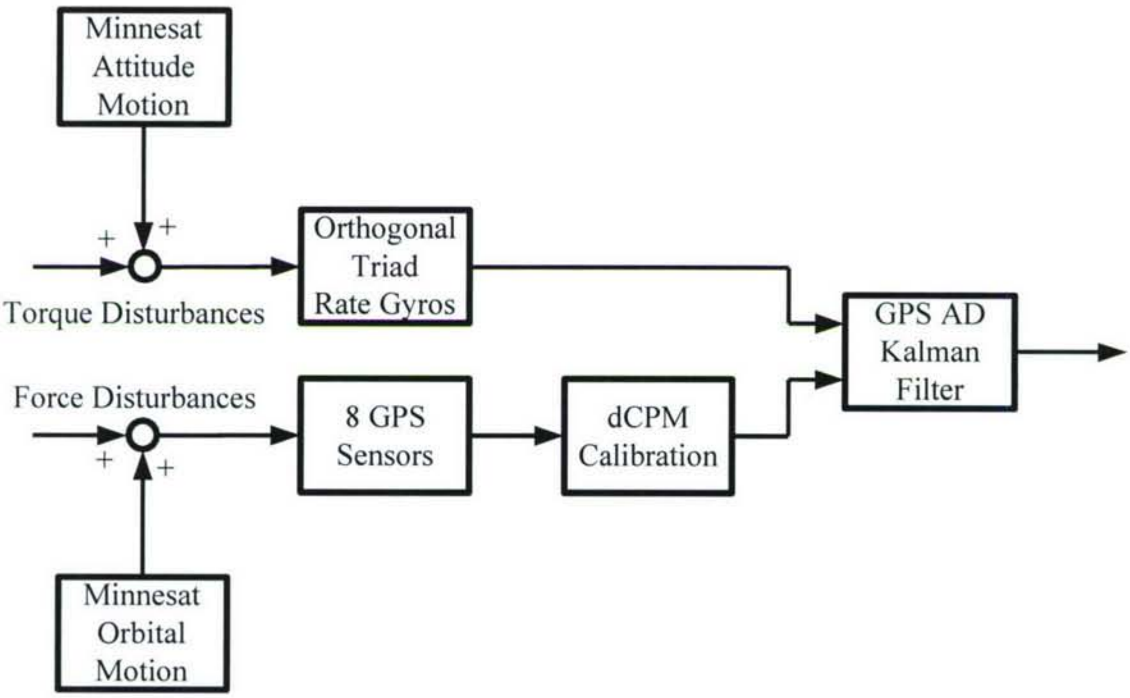

Figure 7. GPS AD System

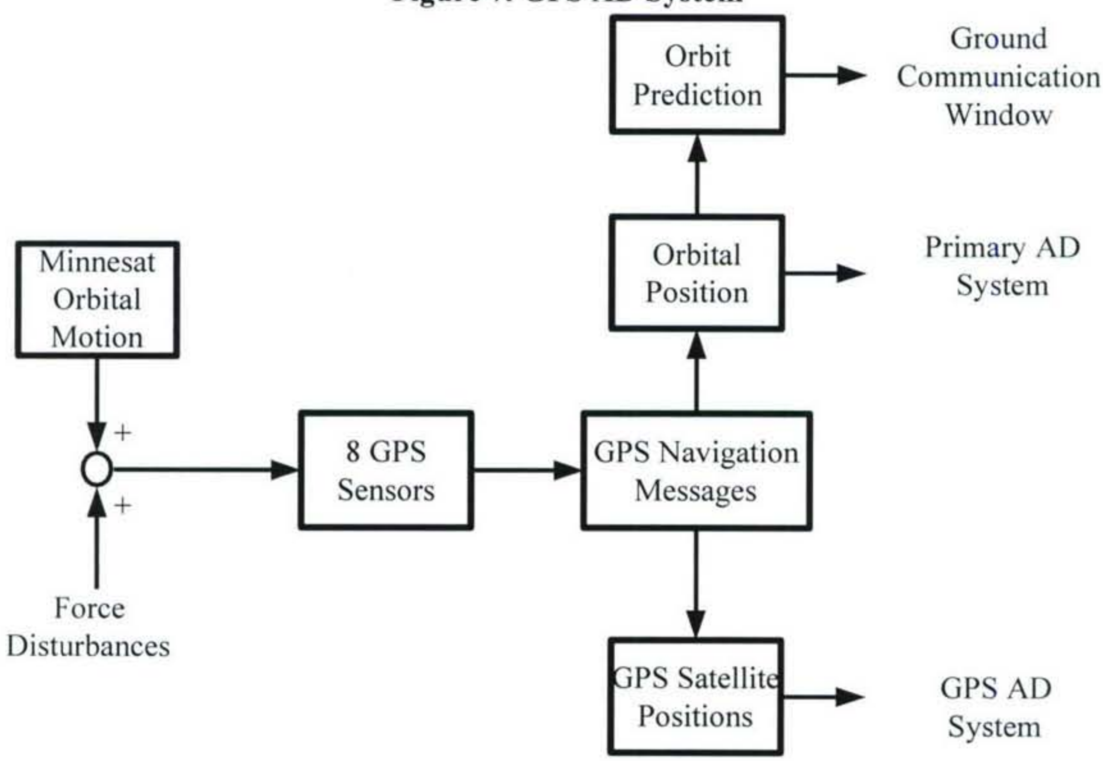

Figure 8. Navigation System

KALMAN FILTER DESIGN

An AD system consists of a set of sensors to measure the vehicle's motion, dynamic models of the vehicle's motion, models of the sensor characteristics, and a filter that blends the sensor measurements using the models to estimate the vehicle's attitude. In general, sensor measurements are corrupted by errors such as bias and wide band noise. These errors are time varying and can fluctuate due to factors such as temperature variations and mechanical vibrations. Furthermore, the sensors can be misaligned from their intended orientation due to manufacturing errors or mounting errors. Therefore, the attitude filter requires models of the sensor errors to accurately estimate attitude.

In these attitude determination experiments, EKFs are designed to blend rate gyro measurements with either magnetometer or dCPMs to estimate Minnesat's attitude in the presence of sensor errors (Figure 9). Rate gyros are high bandwidth sensors and can be used to estimate the attitude of a vehicle performing rapid maneuvers. However, rate gyro measurements are subject to bias and wide band noise and the attitude estimates computed using these measurements result in unbounded errors.[5]

Magnetometers and GPS sensors are low bandwidth sensors and can not be used to estimate the attitude of a vehicle performing rapid maneuvers. These sensor measurements are independent of the rate gyro measurements and measurement errors. Therefore, the magnetometer and GPS sensor measurements can be used to estimate the rate gyro bias and bound the gyro-based attitude estimation errors. The Kalman filter is used to blend the measurements from these sensors to compute more accurate attitude estimates as compared to using the sensors individually. The magnetometer and GPS sensors can be thought of as part of an aiding system for the gyro-based attitude estimates.

The general design of the EKFs for both the Primary AD System and the GPS AD System is shown in Figure 10. The Kalman filter blends measurements from multiple sensors to compute

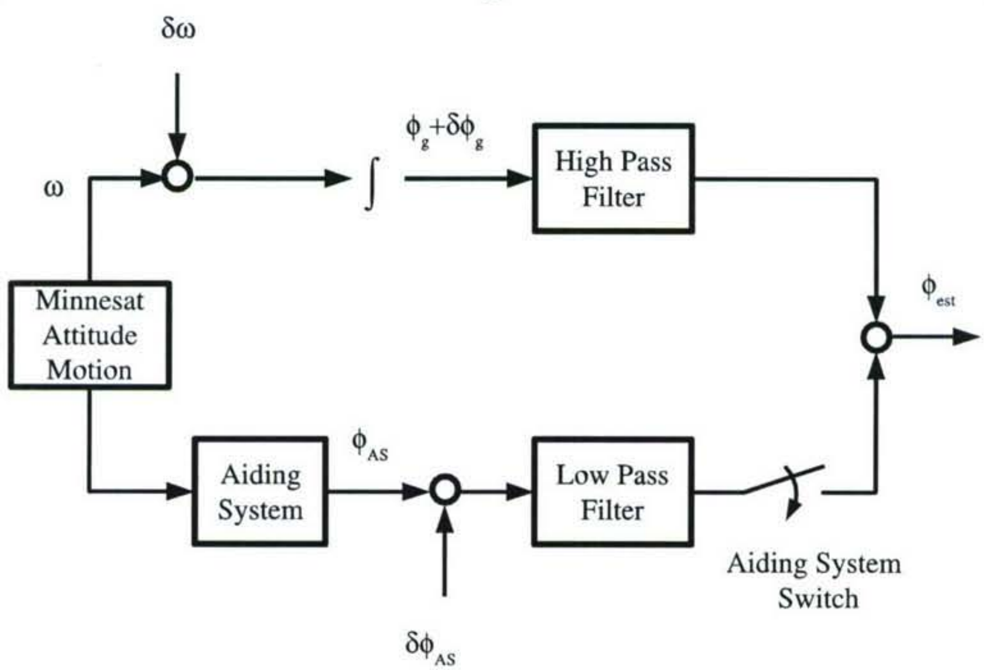

Figure 9. Complementary/Kalman Filter

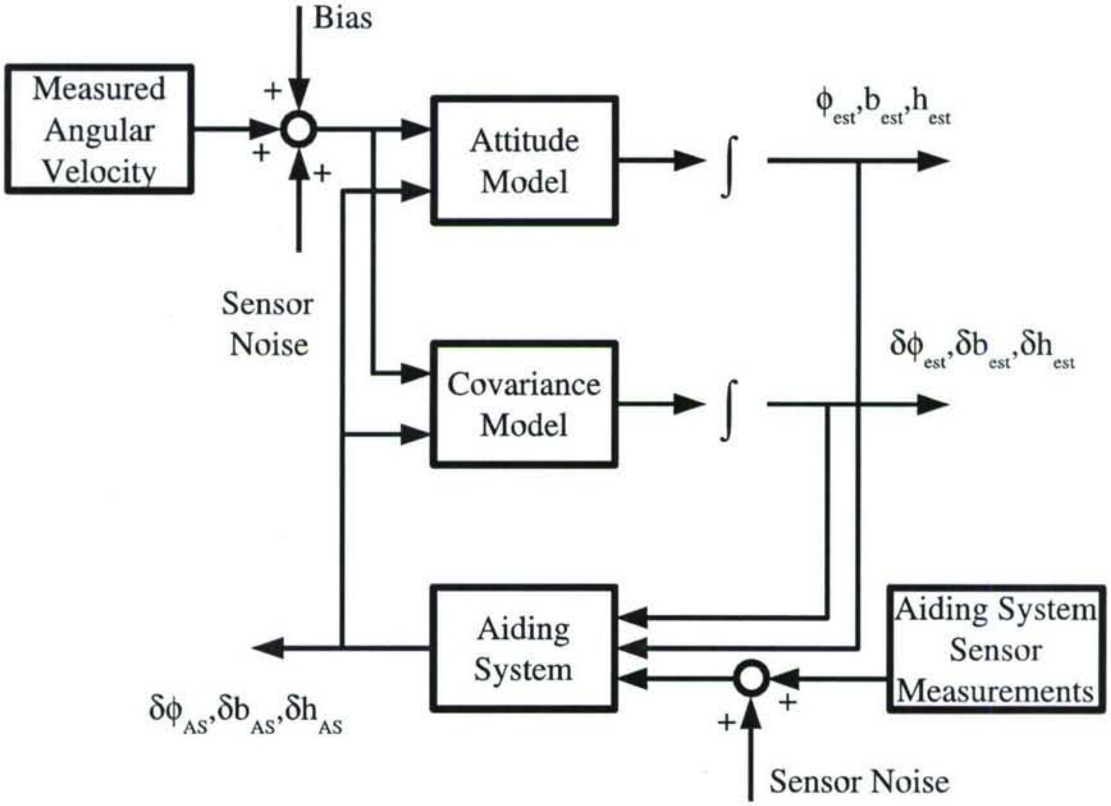

Figure 10. EKF Design

estimates of the state mean vector and the state covariance matrix using a time update and a measurement update.[6] The time update involves propagating estimates of the state mean vector and state covariance matrix using the rate gyro measurements. The state vector is defined from the dynamic models selected to describe the vehicle's attitude motion. The measurement update involves computing posterior estimates of the state mean vector and state covariance matrix using the aiding system sensor measurements. The measurement update uses a measurement model to relate the aiding system sensor measurements to the state mean vector and state covariance matrix. The time update can be considered as a gyro-based AD system. The measurement update can be considered as a gyro-free AD system.

The EKFs of the Primary AD System and GPS AD System use the same dynamic and covariance models for the time update. The vehicle dynamic models include Euler's equations and quaternion based attitude kinematic equations.[7] Rate gyro measurements are used to propagate the dynamic and covariance models. Therefore, the time update rate occurs at the rate gyro sampling frequency. A rate gyro error model is incorporated into the time update so that the rate gyro bias can be estimated by the aiding system and the attitude errors computed by the gyro-based AD system can be bounded.

The EKFs of the Primary AD System and GPS AD System use different measurement models for the measurement update. The Primary AD System uses a three-axis magnetometer to provide one vector measurement of attitude. The measurement model is designed based on a vector matching algorithm that solves Wahba's problem.[8,9] The measurement update rate occurs at the magnetometer sampling frequency. The GPS AD System uses the calibrated dCPMs to provide at least two vector measurements of attitude. The measurement model is designed based on the LOS vector from an antenna baseline to a GPS satellite. The measurement update rate occurs at the GPS sensor sampling frequency.

In summary, the rate gyro measurements are used in both EKF designs to increase the bandwidth of the gyro-free AD systems, to smooth the attitude solution in between measurement updates, and to provide attitude measurements in the event of aiding system sensor unavailability or failure. The aiding system is used to estimate the rate gyro bias and bound the attitude errors computed by the gyro-based AD system. Euler's equations are included in the dynamic model of the time update to act as a dynamic constraint on the vehicle's attitude model in the event of attitude sensor unavailability or failure.

The attitude estimates computed by the EKF of the Primary AD System are considered the true attitude of Minnesat. Both AD systems use the same rate gyro measurements so that the time update rates for both EKFs are the same. The magnetometer and GPS sensor measurements are synchronized so that the measurement update rates for both EKFs are the same. The performance of the GPS AD System is evaluated by comparing the estimates of the state mean vector and state covariance matrix for both AD systems.

4. SUMMARY

The University of Minnesota nanosatellite, Minnesat, is designed to perform ultra-short baseline GPS attitude determination experiments in low Earth orbit. This paper has described the design of both the Primary Attitude Determination System and the GPS Attitude Determination System that will be tested onboard Minnesat. The intent of the University of Minnesota Small Satellite Program is to complete the design and development of Minnesat by March 2007.

5. REFERENCES

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